Quasi nonlinear plasma wakefield experiments at ATF (AE50): Status report

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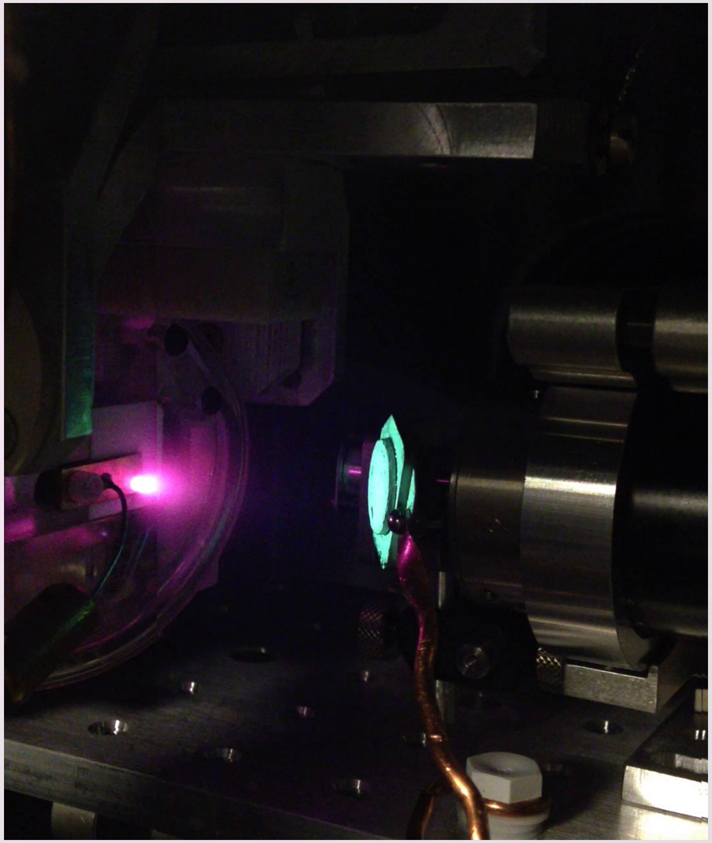

Plasma discharge at ATF

Two regimes of PWFA: Linear and Nonlinear

PWFA regime	Advantage	Disadvantage
Linear	-Can drive plasma oscillations resonantly to reach higher fields and better transformer ratios using ramped bunch trains	-Non linear radial focusing -Radially dependent acceleration
Non linear	-Linear ion focusing -Acceleration independent of transverse position	-Amplitude dependent period -Large wavebreaking -Small window for positron acceleration

Can we exploit advantages of both?

Quasi nonlinear regime of PWFA

Condition for blowout: $\dfrac{n_b}{n_0} > 1$

A measure of nonlinearity is the normalized charge:

$$\tilde{Q} \equiv \frac{N_b k_p^3}{n_0} = 4\pi k_p r_e N_b \begin{cases} << 1, & \text{linear regime} \\ > 1, & \text{nonlinear "blowout".} \end{cases}$$

Using highly focused, low emittance low charge beams, can achieve:

$$\tilde{Q} < 1 \qquad \frac{n_b}{n_0} > 1$$

Experimental proposal

What would be a good experiment to demonstrate this effect?

Goals:

1. Resonantly drive the plasma wakefield response with the use pulse trains and observe effect in the momentum spectrum
2. Observe guiding of an electron pulse train through the plasma

How:

1. Generate pulse trains of electron beams with spacing on order of plasma wavelength
2. Satisfy the beam density condition
3. Need plasma source

Beam-plasma interaction experiments at ATF

- "Seeding of Self-Modulation Instability of a Long Electron Bunch in a Plasma." Fang, Y. *et al Phys. Rev. Lett.* **112** 045001(2014)
- "Generation of Trains of Electron Microbunches with Adjustable Subpicosecond Spacing," Muggli, p. *et al Phys. Rev. Lett.* **101** 054801 (2008)
- "High-gradient plasma-wakefield acceleration with two subpicosecond electron bunches," Kallos, E. *et al Phys. Rev. Lett.* **100** 074802 (2008)
- "Experimental Study of Current Filamentation Instability," Allen, B. *et al Phys. Rev. Lett.* **109** 185007 (2012)

- For all of these experiments, plasma density is greater than beam density
- To get higher beam densities, need to focus beam better:

$$\sigma_r \approx 100\mu m \to \sigma_r \approx 5\mu m$$

ATF capabilities

Nominal ATF parameters with PMQs	
Energy	60 MeV
Current	100 A
Normalized emittance	1-2 mm-mrad
RMS energy spread	<0.1%
RMS transverse beam size	<5 microns
Waist beta function	1-2 mm
Pulse train bunch spacing (Δz)	~200-500 microns
Plasma density	~10^{15}-10^{17} cm^{-3}

For a matched bunch in a pulse train, $\Delta z = \lambda_p = 400\mu m$, $\frac{n_b}{n_p} = 5$ and $\tilde{Q} = 0.1$

Quasi nonlinear experiments at ATF is a go!

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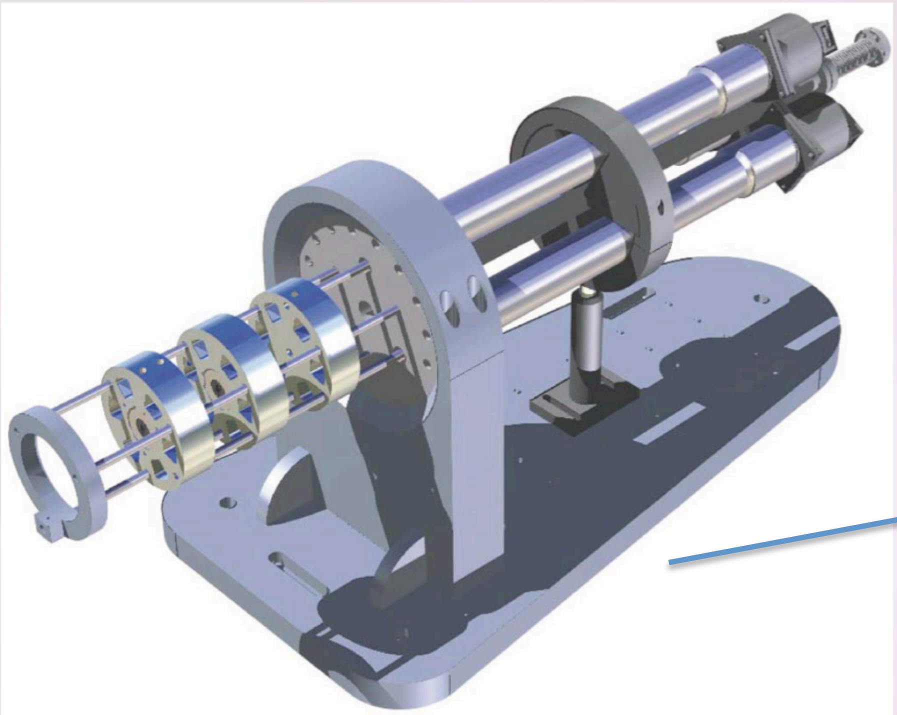
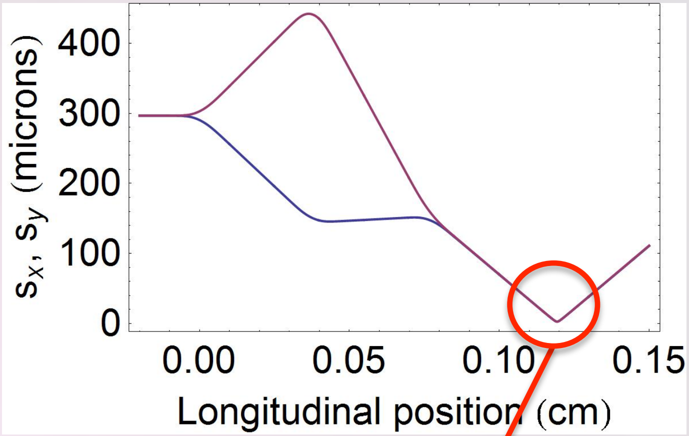
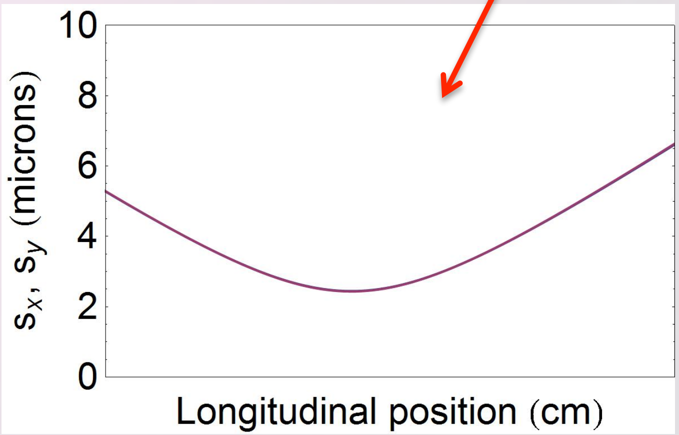
Permanent Magnet quadrupoles







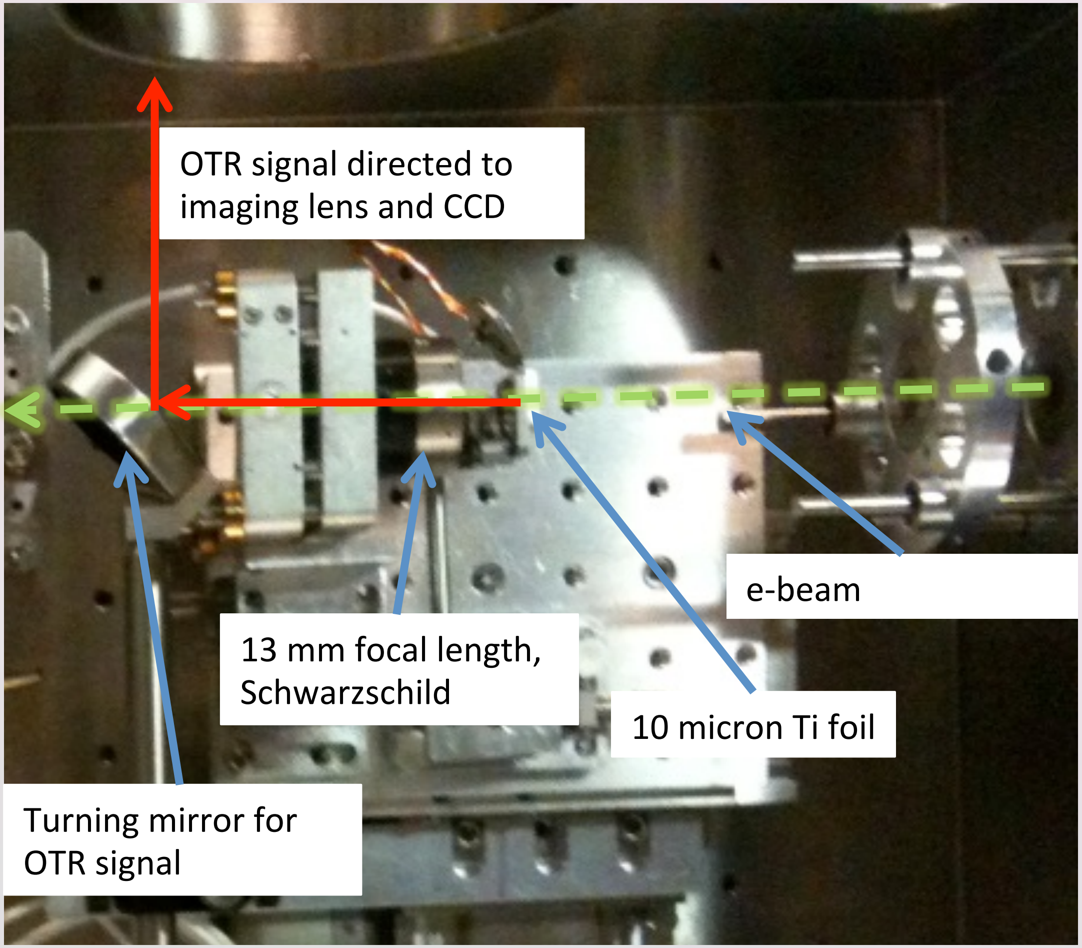
Adjustable focal length PMQ triplet:

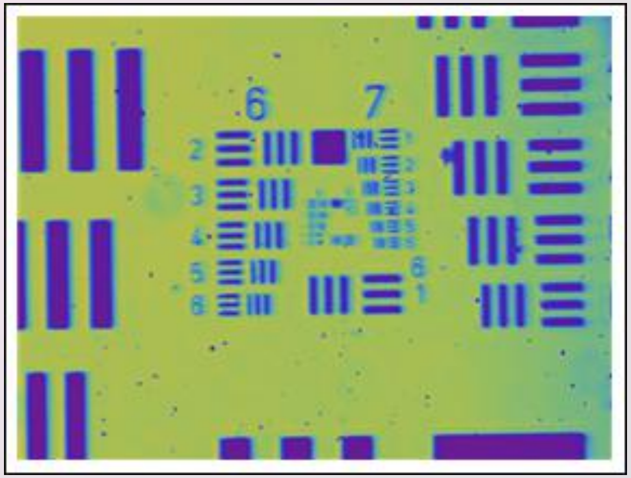
- Three 1 cm PMQs
- Gradients of ~270 T/m and 560 T/m
- Effective focal length of ~8cm @ 58MeV

Focusing properties of PMQ triplet, optimized with Elegant

Measuring micron scale beams

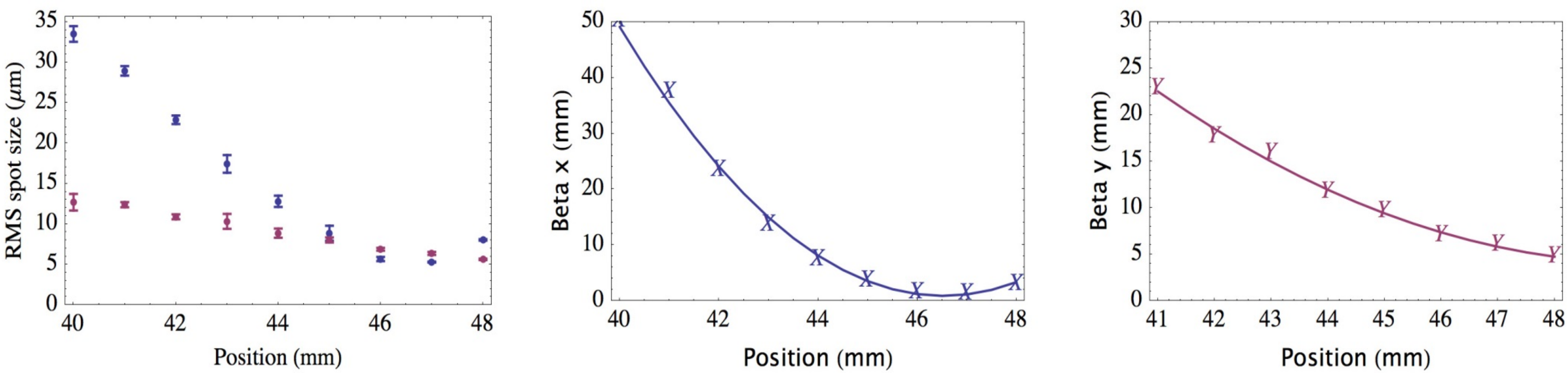
To measure beams we employ a high resolution OTR imaging system consisting of a 10 micron Ti foil, Schwarzschild objective, imaging lens and CCD camera.





Optical resolution test of imaging system using 1951 USAF target demonstrating ability to resolve objects smaller than 3 microns

Transverse beam measurements from OTR



Date: 20140522
Scan identifier: OTR_scan_01
True_RMS: 0.15

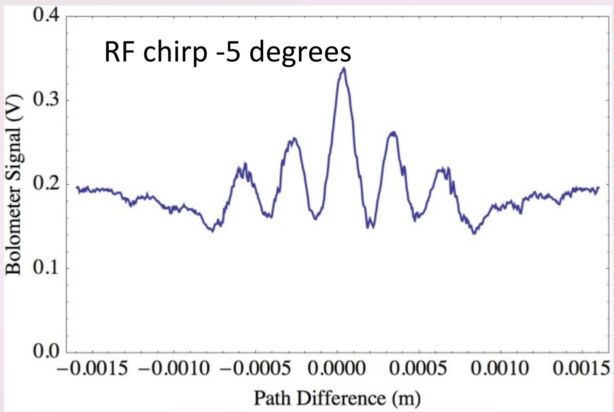
Fitted Beam parameters in x direction		
ϵ_{nx}	mm–mrad	2.51
$\sigma_{x,0}$	μm	4.45
$\beta_{x,0}$	mm	0.884
$s_{x,0}$	mm	46.5

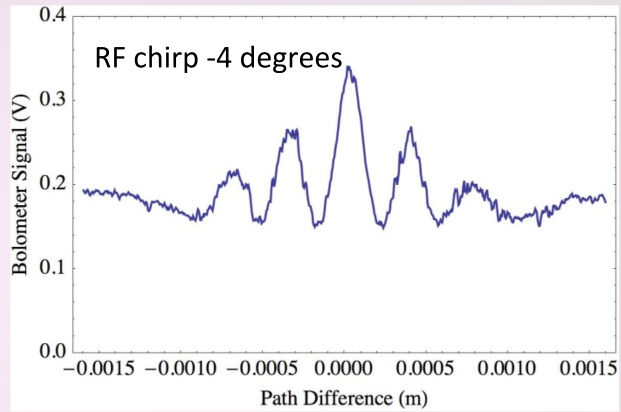
Fitted Beam parameters in y direction		
ϵ_{ny}	mm–mrad	0.755
$\sigma_{y,0}$	μm	5.23
$\beta_{y,0}$	mm	4.07
$s_{y,0}$	mm	49.7

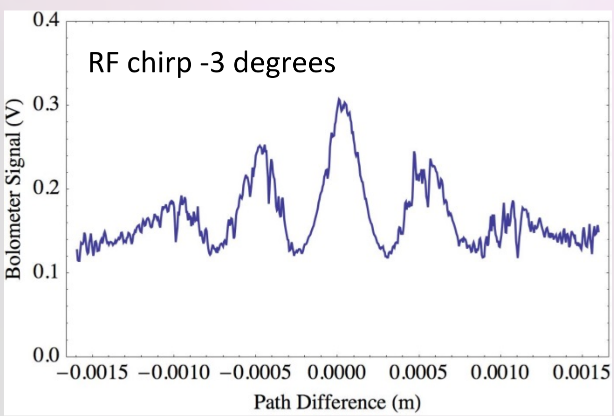
Electron beam mask for pulse train generation

Using mask in dispersive section pulse trains of variable spacing can be generated

Picture of the mask (left) and image of masked beam on phosphor screen (right)





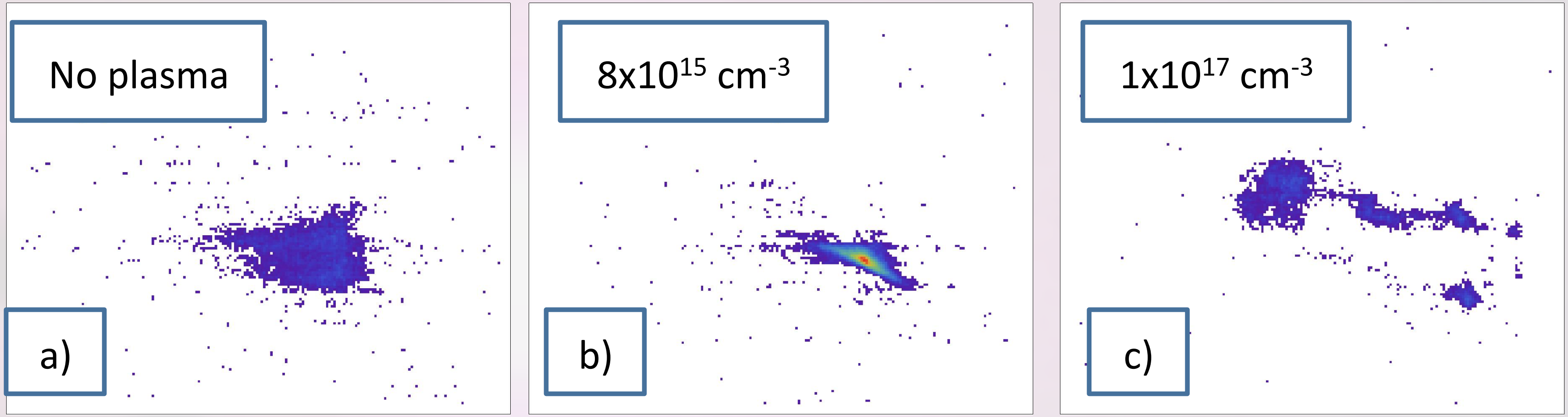


RF phase	Separation (um)
-5	310
-4	370
-3	540

Bunch separation measurements are made by autocorrelation of the CTR signal of the pulse train. Variation of the RF phase (correlated energy spread) allows on to vary bunch separation

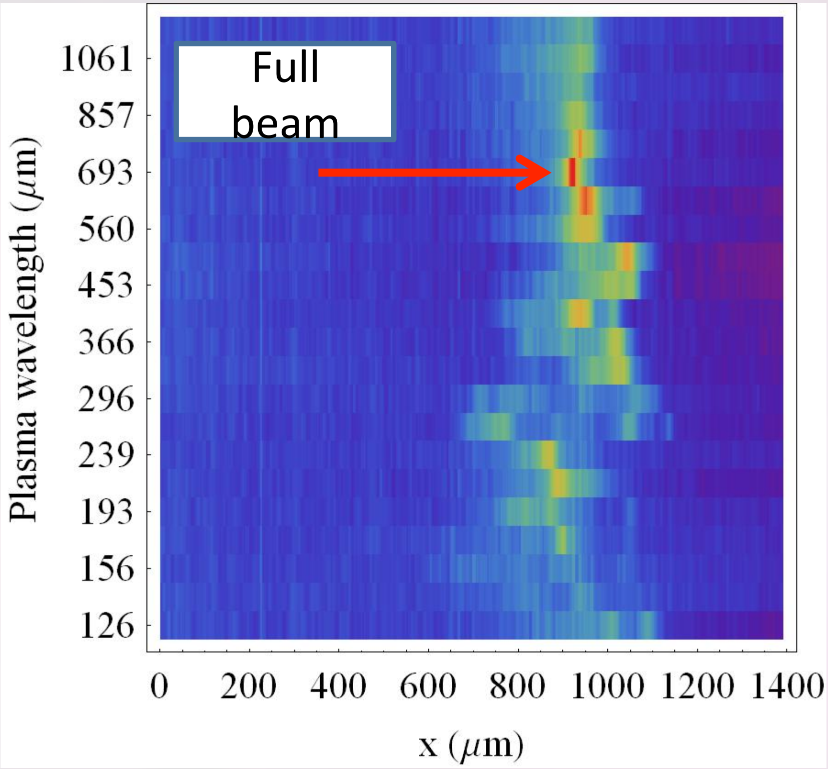
OTR downstream of plasma

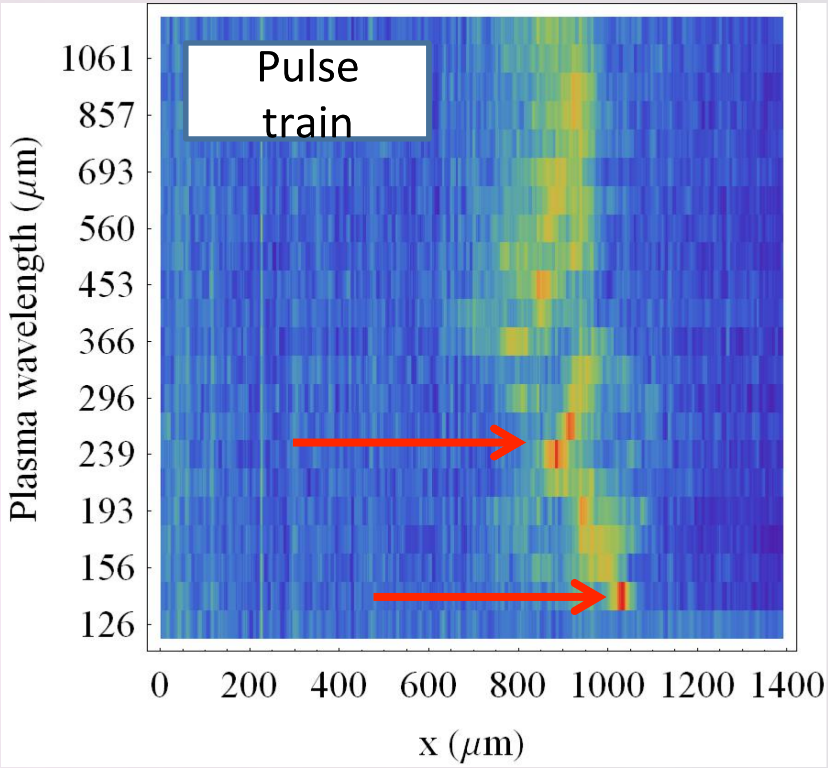
First tests: Using 300 pC, 3 pS long beam, the beam is imaged 5 mm downstream of plasma source (30 mm downstream of waist)



- At best focus (b) beam size is ~30 x 20 microns, ~5 times smaller than with no plasma (a)
- At high density (c) when $k_p\sigma_z > 2\pi$ the beam undergoes break up as consequence of hosing and radial modulation.
- We can study transition from beam breakup to focusing

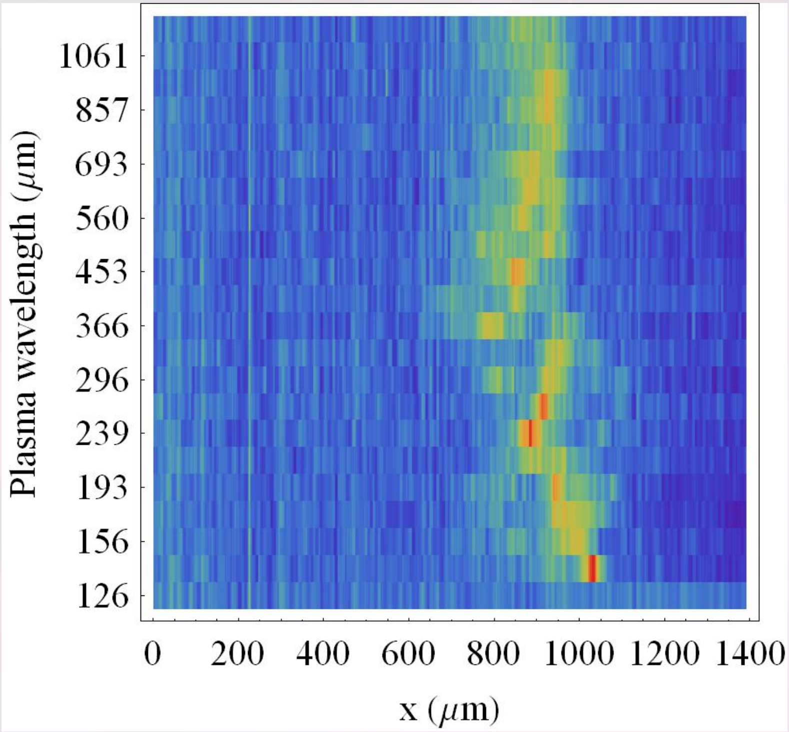
Plasma density scan with long beam and pulse train

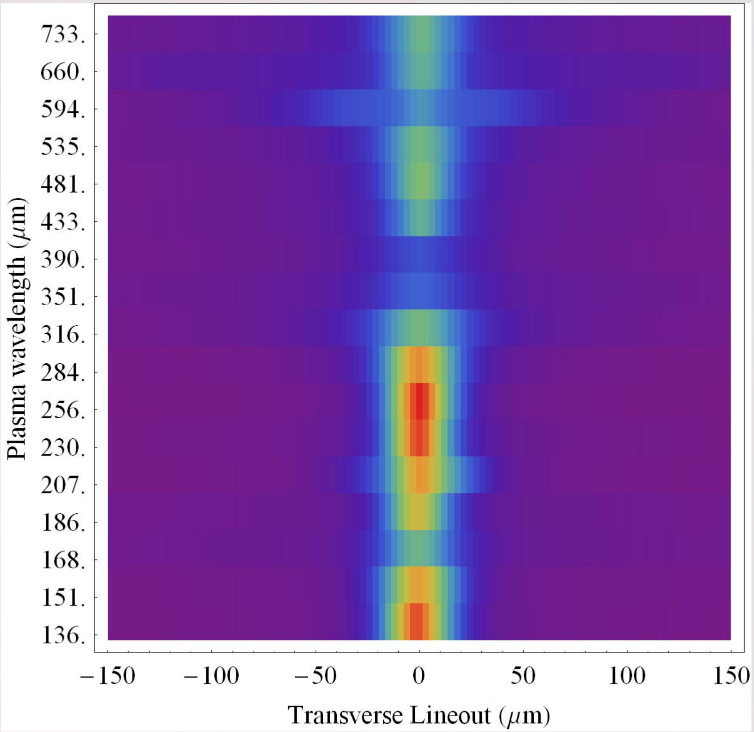




Plasma density is scanned from over a range of densities while OTR images are captured. Each line in (a) and (b) is the integrated lineout of the OTR image in the horizontal direction. In (a) the unmasked, full length beam is used, in (b) a pulse train with 310 micron separation is used. Note the shift to higher densities of the "best" focus occurs (indicated by red arrows).

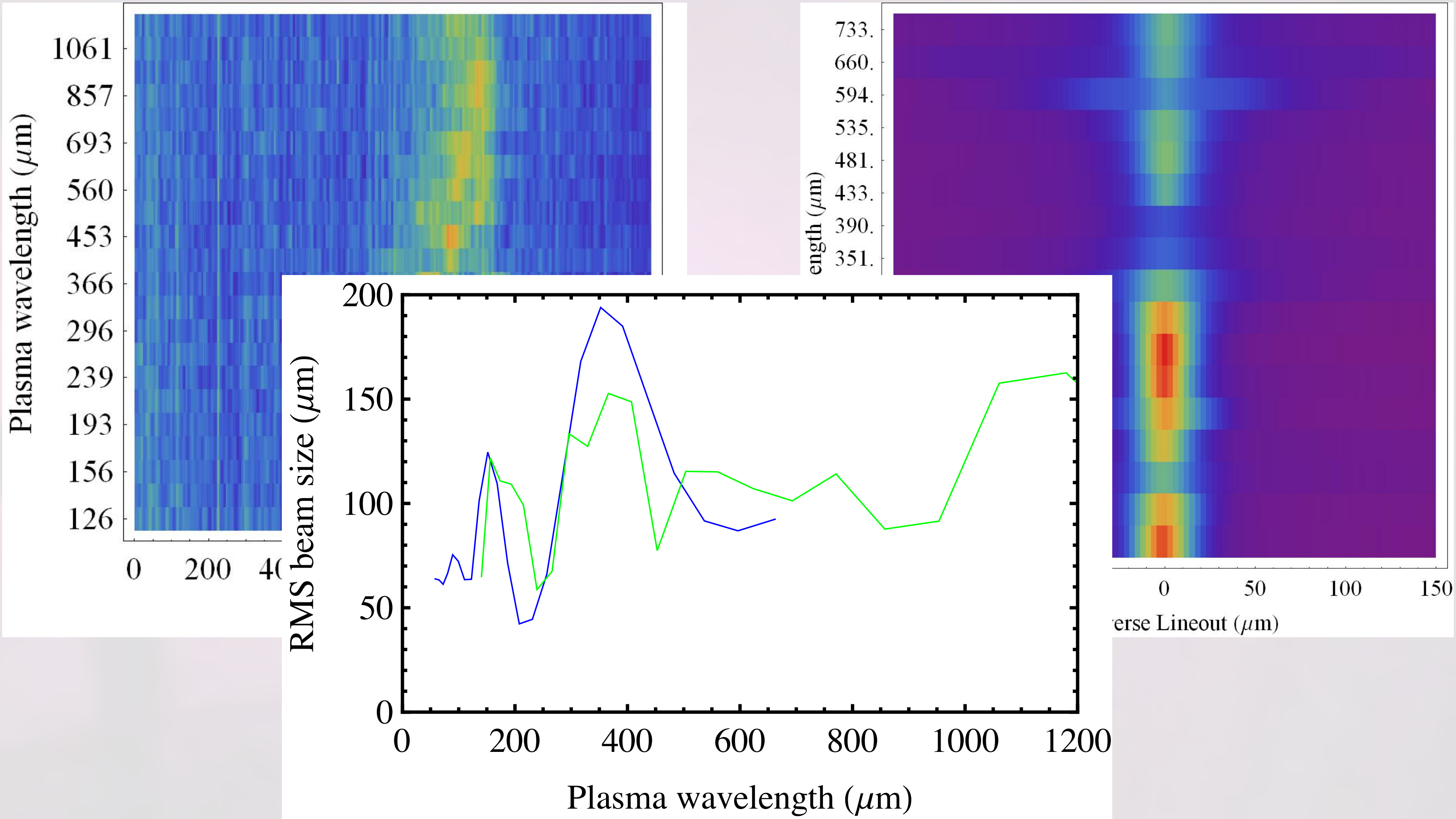
Comparison to 3D PIC simulations





Vorpal (3D PIC code) simulations for a similar beam/plasma parameters show similar character.

Comparison to 3D PIC simulations



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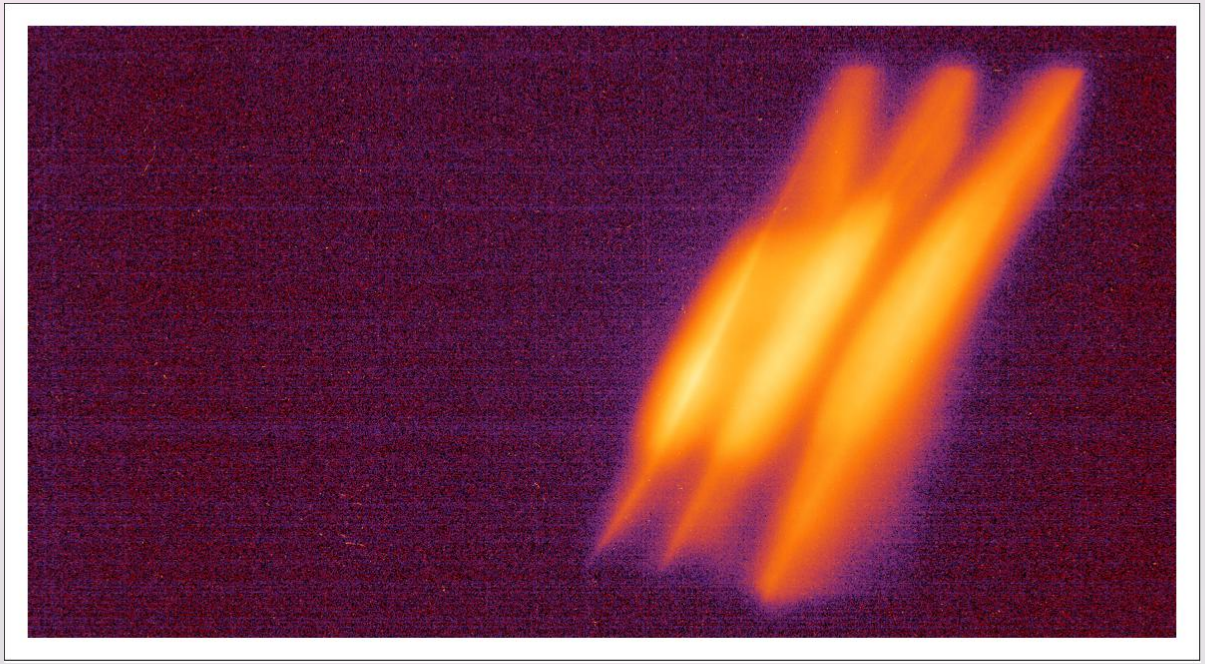
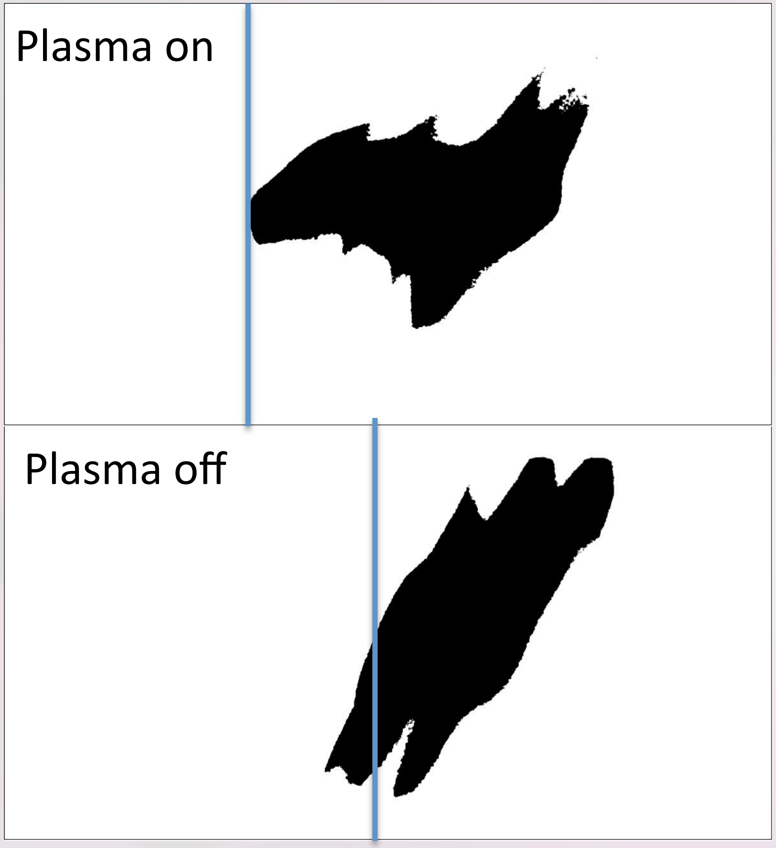
Energy spectrometer measurements

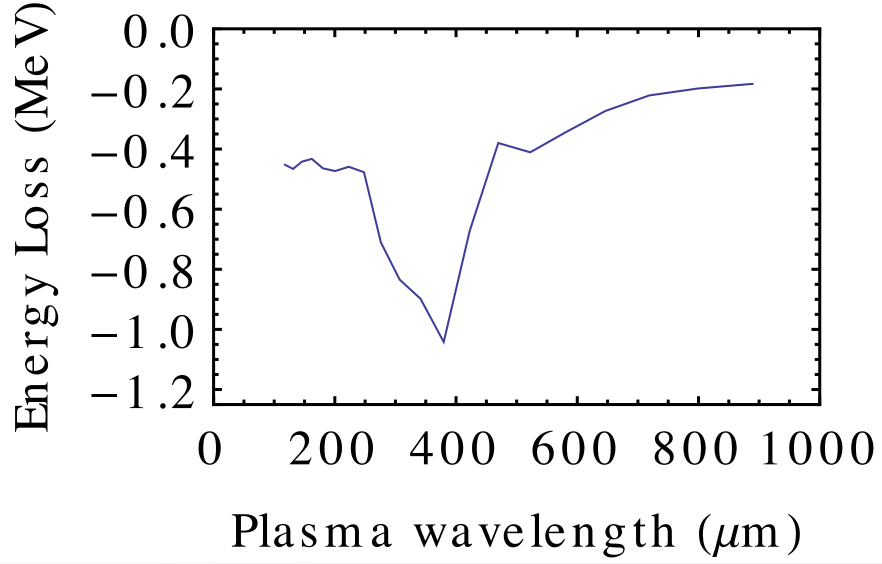
Spectrometer image showing a three bunch train. Relatively large size and tilt are due to difficulty in transporting beam to spectrometer after extreme focusing



56.3 MeV → 58.0 MeV

Energy spectrometer measurements





To investigate a resonant effect, we look at the lowest energy particle after the plasma interaction. Plotting energy of the last particle versus plasma wavelength, we note a strong dip right at a wavelength equal to the spacing of the three bunches (380 microns). The overall energy loss is lower than predicted by simulation by a factor of ~4. Investigations into possible reasons is underway.

Summary

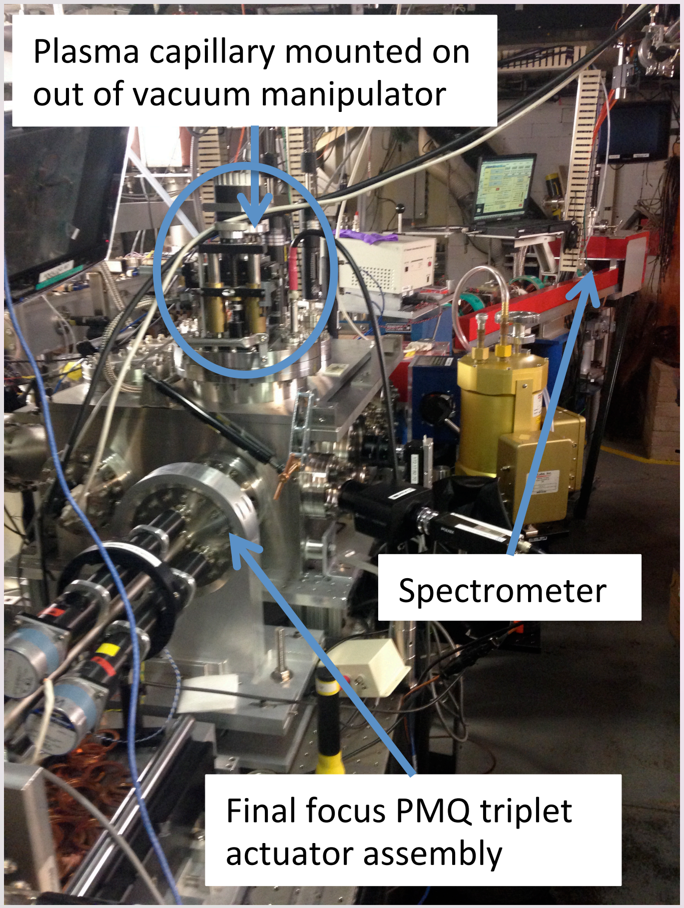
- Quasi nonlinear experiments underway at ATF
- 5 micron beams established
- Hints of resonant excitation of wakefields, and plasma focusing
- Simple test of transverse modulation instability

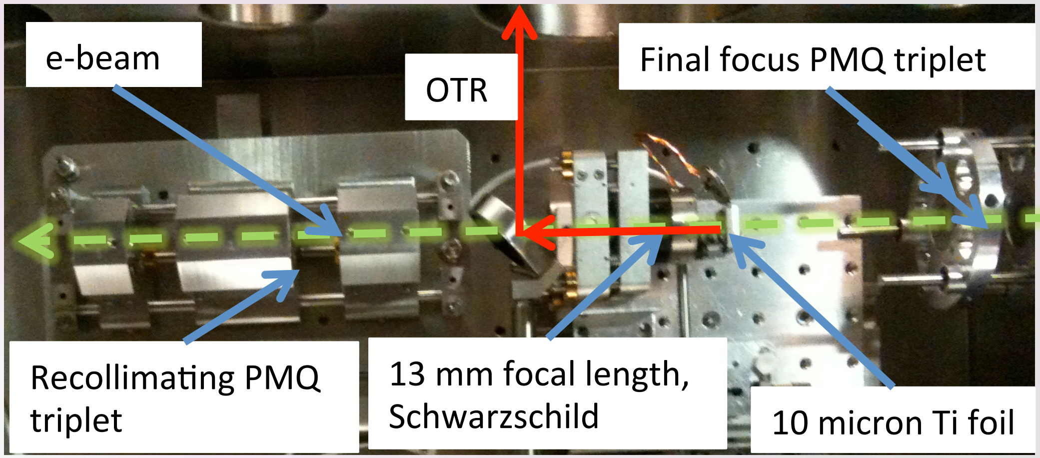
TO DO:

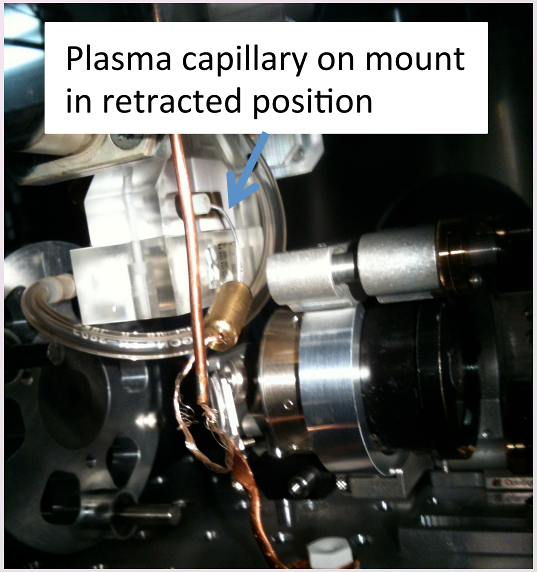
- Need better understanding discrepancy between simulation and data as related to energy shift.
- Possible to improve OTR diagnostic using refractive objective, but requires some minor modifications to plasma source.
- Possible design better TMI experiment

Thanks

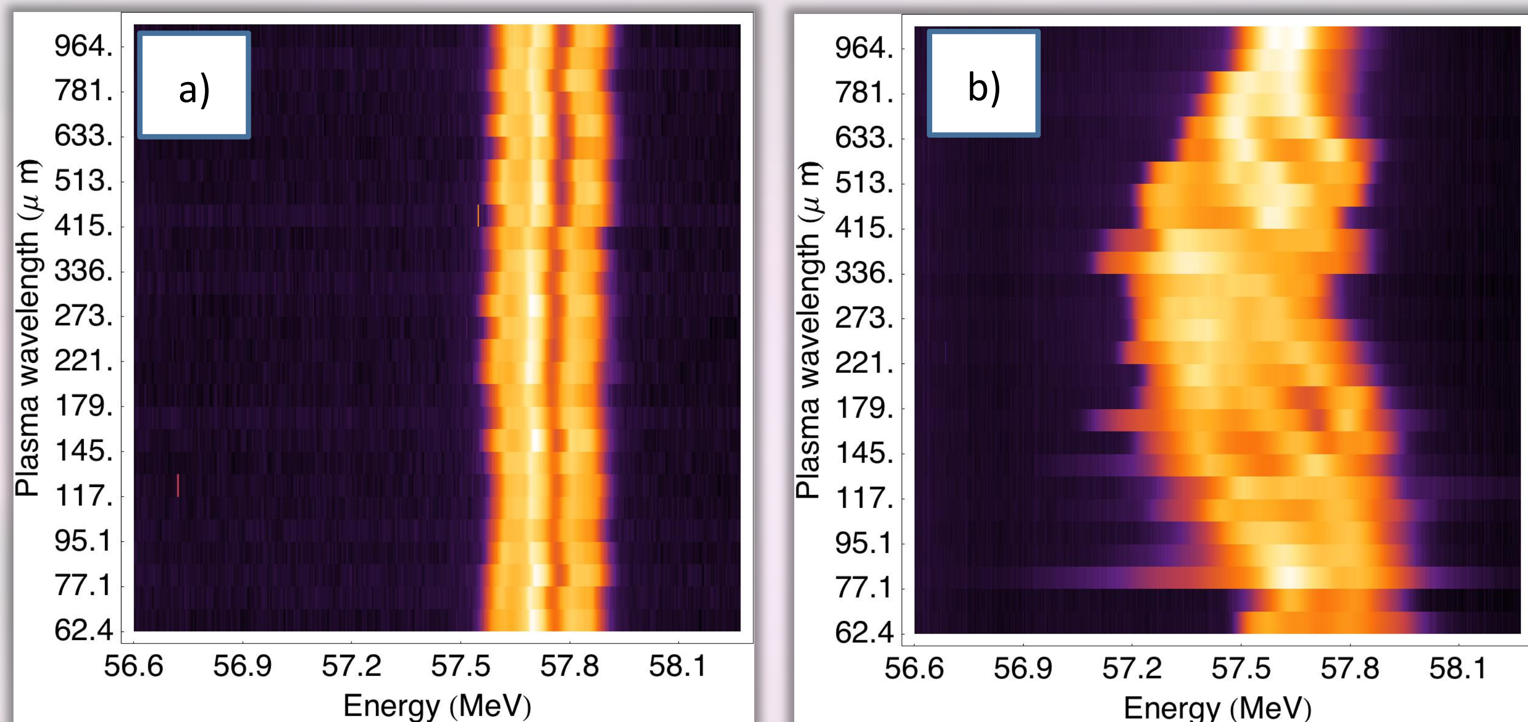
Installation







Energy spectrometer measurements



The above shows the results of passing a 3 bunch pulse train through the plasma while varying the plasma density (b) with a reference with no plasma shown in (a). Each line in (a) and (b) is a lineout of the spectrometer image. There are hints of resonant behavior in (b) but the results are slightly different than what is anticipated from simulation. Further data analysis is underway.

Installation

Need differential pumping to prevent contamination propagating from plasma to linacs and electron gun. Various small apertures make tuning the electron beam difficult.